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Development of adaptable products based on modular design and optimization methods

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Abstract

A new approach is introduced in this research to identify the optimal designs of adaptable products that can be changed, such as reconfigured and upgraded, in the operation stage considering the whole product life-cycle spans based on the modular design and optimization methods. In this new approach, product descriptions in different life-cycle phases are modeled by different configurations, and each of these configurations is described by a set of parameters. Components with similar life-cycle properties are grouped into modules. A hybrid AND-OR tree is used to model all feasible design candidates, different configurations in different life-cycle phases for each feasible design candidate, and parameters for each configuration. A multi-level optimization method is employed to identify the best design solution, its configurations in different life-cycle phases, and parameter values of the relevant configurations based on evaluation considering the whole product life-cycle span. A case study is implemented to demonstrate the effectiveness of the developed new adaptable design approach.

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Keywords: Adaptable product; product life-cycle; modular design; optimization

1. Introduction

Adaptable design approach aims at replacing multiple products with a single adaptable one that can be changed and/or adapted, such as reconfigured and upgraded, during the product operation stage to satisfy the changing customer requirements [1,2].

Since the introduction of this new concept, many adaptable design methods have been developed in the past decade [2]. In this research area, Li et al. [3] introduced new adaptability evaluation measures, including extendibility of functions, upgradeability of modules, and customizability of components, to evaluate different design candidates and to identify the optimal one. Fletcher et al. [4] developed a method to evaluate the adaptability of a product by comparing the actual structure of the product with its ideal structure that can be easily changed. Xue et al. [5] developed an optimization method for identifying the optimal design of an adaptable product when both requirements and product descriptions are changed during the whole product life-cycle span. The method developed by Xue et al. [5] was further improved as a robust adaptable design method considering both the evaluation measures and variations of the evaluation measures in optimization through design of parameters and design of configurations [6].

The objective of this research is to further improve the adaptable design method introduced by Xue et al. [5] by developing a modular design approach considering different life-cycle properties of the components in the adaptable product considering the whole product life-cycle span.

Modular design is a design approach to group similar components of the product into relatively independent modules such that these modules can be disassembled non-destructively from the product [7]. Modular design is often used to build a family of products or different configurations of a reconfigurable/adaptable product [2]. In modular design, similarities of components are primarily evaluated based on design functions and/or manufacturing processes [7]. Since configurations and parameters are changed for an adaptable product during its whole product life-cycle span, a new approach to identify the modules based on similarities of components in life-cycle properties needs to be developed.

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2. Modeling of design requirements and product descriptions

The life-cycle time of a product from its birth to its death is described by a time parameter T whose value is changed from T_{min} to T_{max} representing the time at product purchase and the time at product disposal/recycle, respectively [5]. The life-cycle time parameter T can be assigned with a continuous value, a discrete value, or an integer value.

For an adaptable product, its whole life-cycle span is usually divided into life-cycle phases as shown in Fig. 1. Each of these n life-cycle phases, L_i (i=1,2,...n), is modeled by its design requirements R_i and design solution D_i.

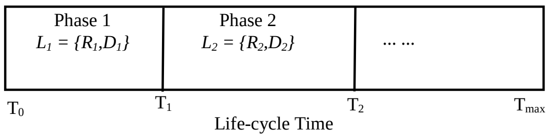


Fig. 1. Product life-cycle phases

Design requirements are defined by qualitative requirements and quantitative requirements. Qualitative design requirements are defined by descriptive text. Typical qualitative design requirements include expected functions, operating constraints, etc. Different requirements can be defined for different life-cycle phases. Quantitative design requirements are defined by expected numerical values and/or numerical constraints.

The overall design solution for an adaptable product is modeled by a collection of different configurations and parameters of these configurations in different life-cycle phases.

Design solution at a particular life-cycle phase of an adaptable product is modeled by a configuration and parameters of this configuration. A configuration is defined by a collection of components organized in a tree data structure as shown in Fig. 2. In this tree, the bottom nodes are used to model components that serve as primitives in the design. Other nodes that are composed of sub-nodes are used to model sub-assemblies and assembly. Both component nodes and assembly nodes are called design nodes. The sub-nodes of a super-node are associated with an AND relation. Among all the design nodes, some nodes can be grouped together to form a module for a particular purpose such as to deliver a design function or to be produced by the same vendor. A design node is associated with design parameters.

When different components, assemblies and modules of the adaptable product are required to satisfy the different requirements in different life-cycle phases, the relevant design nodes are associated with an OR relation in operation (OR-O) as shown in Fig. 3(a). In this case, design solutions in different life-cycle phases are modeled by different operation configurations and their parameters. When the same requirements can be satisfied by different components, assemblies and modules, the relevant design nodes are associated with an OR relation in design (OR-D) as shown in Fig. 3(b). In this case, the design solution for one life-cycle phase can be modeled by multiple design candidates with different design configurations and their parameters. Among all these alternative design solution candidates, only one needs to be selected as the final design solution.

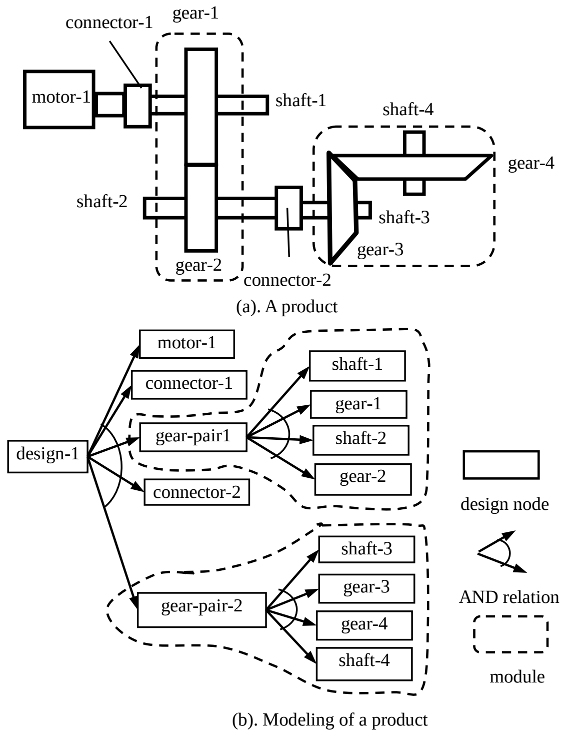


Fig. 2. A Product and its modeling for a particular life-cycle phase

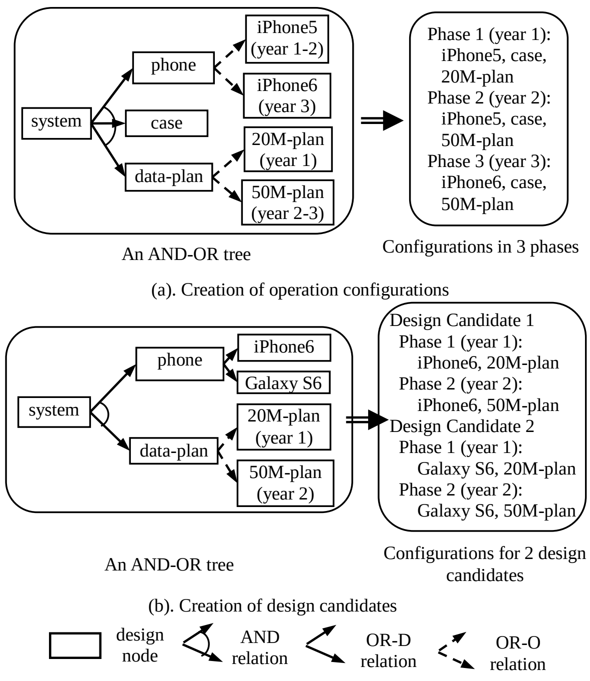


Fig. 3. Creation of design candidates and operation configurations

3. Evaluation of adaptable product

A building unit for modeling an adaptable product can be either a component, a sub-assembly, or a module. A building unit can be modeled by a design node or a sub-tree with design nodes in the hybrid AND-OR tree for modeling partial solutions for the adaptable product. The design nodes in a building unit are associated with only AND relations. Each of these building units can be evaluated by its life-cycle properties. Typical life-cycle properties are listed in Table 1.

Table 1. Examples of typical life-cycle properties.

Category	Life-cycle property	Value
Quantitative	Maintenance frequency	18 months
	Life-span	3 years
	Start time	3rd year
	Time span with reliability over 95%	1.5 years
Qualitative	Degradation of performance	low
	Chance in technology advancement	high

The whole adaptable product is evaluated by a number of evaluation measures considering the product life-cycle span. Since configurations and parameter values of an adaptable product are usually changed throughout the product life-cycle span, an evaluation measure in the life-cycle is also usually changed. The evaluation measure at a particular life-cycle time T in the i-th life-cycle phase is calculated by:

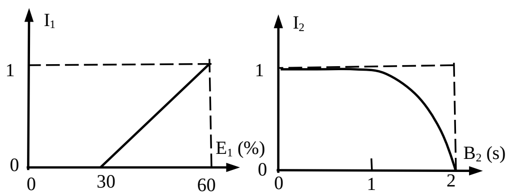
$$E_j(T) = E_j(P_i, T), \quad i = 1, 2, ..., n; \quad j=1, 2, ..., m \qquad (1)$$

where P_i is the collection of parameters for the configuration in the i-th life-cycle phase, m is the number of total evaluation measures, and T is the life-cycle time parameter in the i-th life-cycle phase.

To compare the different evaluation measures in different units, these evaluation measures need to be converted into comparable evaluation indices between 0 and 1, representing levels of satisfaction.

$$I_j(T) = I_j[E_j(T)], \quad j=1, 2, ..., m \qquad (2)$$

The relation between an evaluation measure and an evaluation index can be defined by a linear relation or a non-linear relation as shown in Fig. 4.



E₁: Efficiency of a system — B₂: Braking time to stop a car

(a). A linear relation (b). A non-linear relation

Fig. 4. Relations between evaluation measures and evaluation indices

When the j-th evaluation index, $I_j(T)$, is used to evaluate the adaptable product from a particular perspective at a certain life-cycle time T, the overall evaluation index, $I(T)$, considering all m evaluation aspects at the life-cycle time T can be obtained by:

$$I(T) = \frac{\sum_{j=1}^{m}\left[W_j I_j(T)\right]}{\sum_{j=1}^{m} W_j} \qquad (3)$$

where W_j is the weighting factor between 0 and 1 representing the importance of the j-th evaluation aspect. Fig. 5 shows the two evaluation indices and the overall evaluation index considering the performance and insurance cost for a car.

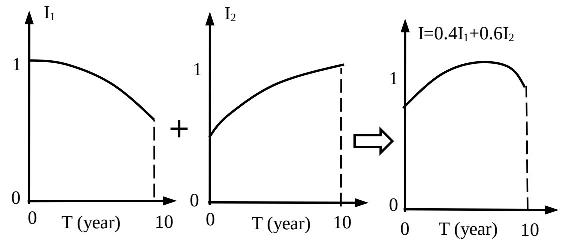


Fig. 5. Individual and overall evaluation indices

The overall life-cycle evaluation index I for the adaptable product considering the whole product life-cycle span can be calculated by:

$$I = \int_{T_0}^{T_{\max}} I(T)dT \qquad (4)$$

4. Design and optimization of the adaptable product

Design and optimization of the adaptable product considering the whole life-cycle span are carried out by organizing the relevant components of the adaptable product into modules and identifying the best design solution that is modeled by different product configurations in different life-cycle phases and parameters of these configurations.

Since modules serve as the important building units for modeling the adaptable product, the first step in the process of adaptable product design is to group the relevant components of the adaptable product into modules. In the traditional modular design approach, the components are usually grouped into modules based on their design functions and production processes to improve the product variety while reducing production cost [7]. In this work, the life-cycle properties are primarily used to group the components that need to be changed in the product life-cycle span into modules. Fuzzy c-means pattern classification method [8] is be used to identify the modules automatically.

Feasible design solutions for an adaptable product is created from the design requirements in the following steps.

1. Modeling of the overall design solution using the hybrid AND-OR tree

2. Creation of alternative design configuration candidates
3. Creation of different operation configurations for different life-cycle phases from each design configuration candidate
4. Selection of parameter values

Since a large number of design configuration candidates, operation configurations, and different parameter values for these configurations can be selected to achieve the design requirements, optimization is employed in this research to identify the best design solution.

A multi-level optimization model is developed to identify the best design configuration solution candidate and its design parameter values considering the whole product life-cycle span. In this optimization model, first the optimal design parameter values for the *k*-th design configuration solution candidate are achieved through parameter optimization.

Find: parameters $\boldsymbol{X_k}$
Optimize: $I^{(k)}$ (5)
Subject to: $\boldsymbol{X_k^{(L)}} \leq \boldsymbol{X_k} \leq \boldsymbol{X_k^{(U)}}$

where $I^{(k)}$ is the selected evaluation index considering the whole product life-cycle, and $\boldsymbol{X_k^{(L)}}$ and $\boldsymbol{X_k^{(U)}}$ represent the lower boundaries and upper boundaries of $\boldsymbol{X_k}$, respectively.

Among all the *p* feasible product design configuration solution candidates, the optimal design solution is obtained through configuration optimization.

Find: the *k*-th design configuration candidate
Optimize: $I = I^{(k)}$ (6)
Subject to: $1 \leq k \leq p$

In this research, parameter optimization can be conducted through numerical search, while configuration optimization can be conducted by genetic programming [9].

The optimization objective functions in Eqs. (5) and (6) are defined by one of the three methods shown in Table 2.

Table 2. Three methods to select optimization objective functions.

Method	Objective function for parameter optimization	Objective function for configuration optimization
Average-case method	Maximize $I^{(k)} = \int_{T_0}^{T_{max}} I(T)dT$	Maximize $I = I^{(k)}$
Best-case method	Maximize $I^{(k)} = I(T)$	Maximize $I = I^{(k)}$
Worst-case method	Minimize $I^{(k)} = I(T)$	Maximize $I = I^{(k)}$

(1) The average-case method

In this method, the average evaluation index considering the whole product life-cycle is used as the objective function for parameter optimization considering one design configuration candidate as shown in Fig. 6(a). The average-case method is normally selected for the optimal design of adaptable product.

(2) The best-case method

In this method, the best evaluation index considering the whole product life-cycle is used as the objective function for parameter optimization considering one design configuration candidate as shown in Fig. 6(b). The best-case method is used when the maximum evaluation measure at one time point in the whole life-cycle span is expected as such as in the design of a racing car to achieve the maximum speed.

(3) The worst-case method

In this method, the worst evaluation index considering the whole product life-cycle is used as the objective function for parameter optimization considering one design configuration candidate as shown in Fig. 6(c). The worst-case method is used when the minimum evaluation measure at one time point in the whole life-cycle span is considered such as in the design of a satellite with the lowest risk of failure.

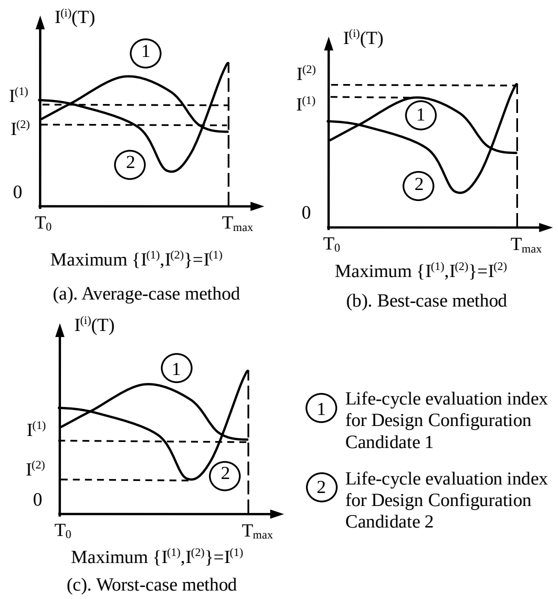


Fig. 6. Three methods for selection of optimization objective functions

5. A case study

The problem of this case study is to design an adaptable equipment that is used to test two newly designed aircraft pumps including one fuel pump and one oil pump. The fuel pump is used to provide fuel to the turbine's combustor, while the oil pump is used to provide lubrication oil to bearings and other fuel system components.

The testing tasks are classified into 3 phases. In Phase I, the fuel pump is tested to quantify leakage and identify leakage spots during a cold start at -54°C. For each test cycle, the fuel pump should be run at low speeds for 1 hour. At least 20 cycles are required to achieve the reliable data. In Phase II, the fuel pump is tested to observe pressure and flow influenced by viscosity of the fuel during standard cold days (i.e., -28°C). For each test cycle, the fuel pump is run at designed speeds that simulate a typical engine cycle for 10 hours. At least 100 cycles are required to achieve the reliable data. In Phase III, the oil pump is tested to observe pressure and flow influenced by viscosity of the oil during standard cold days (i.e., -28°C). For each test cycle, the oil pump is run at designed rotational speeds that simulate a typical engine cycle for 10 hours. At least 100 cycles are required to achieve the reliable data. For Phase I and Phase II, a chamber with capacity of 1 m^3 is required for the fuel pump, while for Phase III, a chamber with capacity of 0.5 m^3 is required for the oil pump. The requirements are summarized in Table 3.

Table 3. Requirements for the three life-cycle phases.

Life-cycle phase	I	II	III
Pump type	Fuel pump	Fuel pump	Oil pump
Test tasks	Leakage	Pressure and flow	Pressure and flow
Temperature (°C)	-54	-28	-28
Chamber capacity (m^3)	1	1	0.5
Duration for each cycle (hour)	1	10	10
Number of cycles	20	100	100
Number of months	1	6	6

The testing equipment is primarily composed of a chamber to place the pumps and a refrigeration unit to keep the low temperature in the chamber. A fan is installed on the top panel of the chamber to provide air circulation. For Phase I, a window is required for the chamber. For the refrigeration unit, a cryogenic system with either liquid nitrogen (LN_2) or liquid carbon dioxide (LCO_2) is considered for Phase I, and a mechanical refrigeration system with either single stage system or cascade system is considered for Phase II and III. The hybrid AND-OR tree considering design configuration candidates and operation configurations in different phases is shown in Fig. 7.

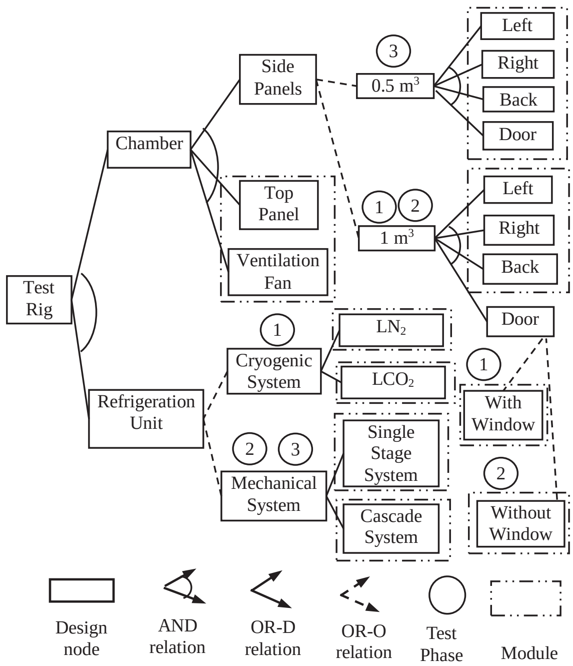


Fig. 7. A hybrid AND-OR tree

In this research, the components that do not need to be separated in different life-cycle phases are grouped into modules such that sophisticated interfaces are not designed to reduce the manufacturing effort. For example, the top panel and the air circulation fan are grouped into a module, the three side panels and the door for phase III are grouped into a module, and the three side panels for phases I and II are grouped into a module. Some modules and the test equipment modeled by modules are shown in Fig. 8.

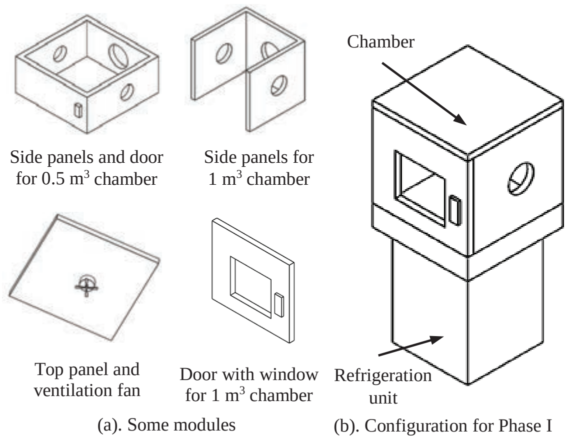


Fig. 8. Modules and test equipment modeled by modules

From the hybrid AND-OR tree shown in Fig. 7, four design configuration candidates, as shown in Table 4, are generated using the OR-D relations given in this figure. All the design nodes for the chamber are used for these candidates. Among the four design configuration candidates, the first one has been selected based on evaluations to all these design configuration candidates.

Table 4. Design configuration candidates.

No.	Design nodes
1	**Nodes for chamber, LN_2 (Phase I), single stage (Phases II and III)**
2	Nodes for chamber, LCO_2 (Phase I), single stage (Phases II and III)
3	Nodes for chamber, LN_2 (Phase I), cascade system (Phases II and III)
4	Nodes for chamber, LCO_2 (Phase I), cascade system (Phases II and III)

For the panels of the chamber, low pressure vacuum space between two walls is considered to reduce the heat loss due to gas conduction of air. In addition, radiation shields between two walls are also considered to reduce the heat loss due to radiation. In this case study, these two parameters are selected as design parameters for the optimization.

Two design parameters:

- *P:* Vacuum pressure (Pa), real number
- *n:* Number of radiation shields, integer

Two evaluation measures are selected as:

- C_p: Product cost ($)
- C_o: Operating cost ($)

For the vacuum pressure, *P*, between two walls of the chamber panels, when it is high (i.e., poor vacuum condition), the gas molecules are close leading to heat transfer by gas conduction. With the decrease of vacuum pressure (i.e., improvement of vacuum condition), the heat loss due to gas conduction is also reduced. When the vacuum pressure is below a threshold, structure supports then need to be designed between the walls. In this case, the decrease of vacuum pressure can lead to increase of the heat loss due to conduction through the supports. Therefore an optimal vacuum pressure needs to be achieved.

For the number of radiation shields, *n*, between two walls of the chamber panels, when only small number of radiation shields are used, these radiation shields can “float freely” between the walls. An increase in the number of radiation shields can lead to decrease of heat loss due to radiation. As the number of shields increases, mesh spacers are designed to prevent the shields from contact each other. When a large number of shields are required, these shields need to be compressed to fit in the space between the walls. In this case, an increase in the number of radiation shields may lead to increase of heat loss due to conduction. Therefore an optimal number of radiation shields needs to be achieved.

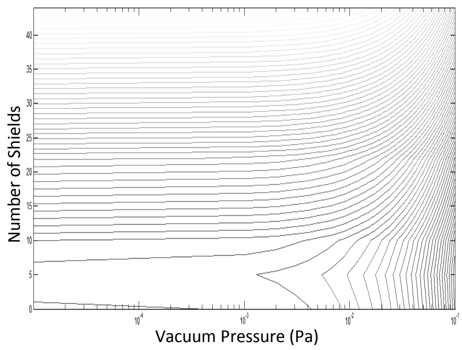
In this case study, thermal dynamics equations are used to calculate the heat loss considering different values of vacuum pressure and number of radiation shields. The various heat loss measures considering all the three life-cycle phases are further converted into the consumptions of LN_2 and electricity. The operating costs are achieved from the consumptions of LN_2 and electricity. The product cost is calculated considering different conditions for vacuum pressure (i.e., different processes to achieve the vacuum pressures) and number of radiation shields (i.e., free floating, with spacers, and with compression).

The total cost, C, considering both the product cost, C_p, and the operating cost, C_o, for the all three life-cycle phases is selected as the optimization objective function.

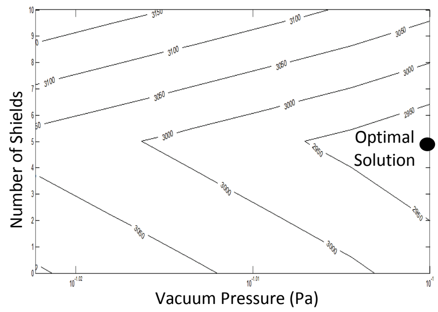
$$\text{Min } C = C_p + C_o \tag{7}$$

The optimal design parameter values are identified as (Fig. 9):

- Vacuum pressure: $P = 0.1$ (Pa)
- Number of radiation shields: $n = 5$



(a). Whole optimization space



(b). Partial optimization space with the optimal solution

Fig. 9. Optimization of two design parameters

6. Conclusions

A new design approach is introduced in this research to identify the adaptable product based on the modular design and optimization methods. Characteristics of this new design approach are summarized as follows.

1. Modular design method is effective to group the components with same/similar life-cycle properties into modules. Since components within a module don’t need to be disassembled/assembled in different product life-cycle phases, sophisticated interfaces are not required for the components in the same module. Therefore the design and manufacturing effort for these components can be reduced.
2. Optimization is effective to identify the optimal design configuration candidate, optimal operation configurations in different life-cycle phases, and parameter values of these configurations. The hybrid AND-OR tree is an effective data structure to model various design configuration candidates, operation configurations and product parameters.

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